Soil Water Depletion—Yield Relationships of Irrigated Sorghum, Wheat, and Soybeans

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ABSTRACT

APPROXIMATELY 4 billion m^3 of groundwater is pumped annually to irrigate sorghum, wheat and soybeans grown in the fine-textured soils of the Southern High Plains. Declining groundwater storage and the high costs of pumping necessitate that water be applied only when it is needed to prevent appreciable yield reductions. Relationships between soil water depletion and grain yields provide a rational basis for scheduling irrigations based on soil water in the major root zone.

Relationships between soil water depletion on Pullman clay loam and yields of grain sorghum, winter wheat and soybeans were derived from 12-crop years of irrigation water management research conducted at the USDA Southwestern Great Plains Research Center, Bushland, Texas. Significant curvilinear relationships, which were fit by the general quadratic equation, were obtained in all years. Measured soil water depletion in the 0- to 120-cm depth accounted for 57 to 99 percent of the treatment yield variability within years.

Depletion of soil water in the 0- to 120-cm depth to -15 bars potential resulted in best estimate relative yields of 73 percent for adequately irrigated grain sorghum, 80 percent for winter wheat, and 47 percent for soybeans. The shape of the depletion-relative yield curves in the drier-than-normal seasons were similar for the three crops. However, in the 20 to 70 percent relative yield range, soil water depletion in the 0- to 120-cm profile was approximately 2.7 cm greater for wheat and sorghum than for soybeans. The lowest soil water contents measured in the 0- to 120-cm profile under prolonged stress were 1.3, 4.6, and 5.6 cm below -15 bars potential for soybeans, grain sorghum and winter wheat, respectively. Based on depletion to below -15 bars, plant available water exceeded the -1/3 to -15 bar range by 8.3 percent for soybeans to 35.7 percent for winter wheat.

The relationship between soil water depletion and relative yields of grain sorghum obtained from a graded furrow study was similar to relationships previously obtained from level border studies. Results indicate that data obtained from level border plots can be applied directly to graded furrow irrigations on similar soils in the Southern High Plains.

INTRODUCTION

The effect of soil water depletion on yields is a major consideration in scheduling irrigations. Frequent irrigation, when the soil profile is moderately wet, can result in excessive and inefficient use of water while excessive drying of the profile before irrigation can result in major yield reductions.

Jensen and Sletten (1965a) reported that grain sorghum yields on Pullman clay loam were not materially affected by soil water level if the available level in the 0- to 120-cm root zone was maintained above 30 percent. They scheduled irrigations when the weighted mean soil water potential in the 0- to 120-cm depth was -1.5, -4, and -9 bars. (The 0- to 30-, 30- to 60-, 60- to 90-, and 90- to 120-cm depth increments were weighted 4, 3, 2, and 1, respectively, to correspond with an approximate depletion pattern of 40, 30, 20, and 10 percent for the four successive depth increments.) Yields were not affected when depletion decreased the weighted soil water potential from -1.5 to -4 bars but a further decrease to -9 bars decreased 4-yr average yields from 7,340 to 6,200 kg/ha.

In a similar study with winter wheat, Jensen and Sletten (1965b), reported that yields were not affected when depletion decreased weighted soil water potential from -1.5 to -4 bars. A further decrease to -9 bars decreased 3-yr average yields from 2,960 to 2,810 kg/ha.

Musick and Sletten (1966) compared soil water depletion-yield relationships for grain sorghum grown on Pullman and Richfield clay loam soils. Grain yields were not reduced significantly until available soil water in the 0- to 120-cm depth was depleted below 5.1 cm between boot stage and dough stage of grain development. The 5.1 cm available in the 0- to 120-cm depth corresponded to 25 percent available in the Richfield and 30 percent in the Pullman.

Musick et al. 1963, reported that irrigated winter wheat yields grown on Richfield clay loam at Garden City, Kansas, were not reduced until soil water in the 0- to 120-cm depth was depleted to the wilting point and approached the wilting point in the 180-cm profile during grain filling. Apparently, winter wheat had a greater ability than grain sorghum to deplete available soil water from the deep silt loess subsoil of the Richfield before significantly decreasing yields. This ability may have been associated with a deeper root system.

Grain sorghum and winter wheat are the two major irrigated crops grown on the fine-textured soils of the Southern High Plains. Each crop is grown on approximately 400,000 ha of irrigated Pullman clay loam and related soils. Soybeans, a minor crop by comparison, is grown on about 50,000 ha.

The Pullman and related fine-textured soils are slowly permeable and are almost entirely irrigated by

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the graded furrow method. Water intake during irrigation usually ranges from 7 to 13 cm and depth of wetting from 45 to 90 cm. The preplant irrigation, the first irrigation after major tillage, is usually the largest applied and may wet the soil to 120-cm depth. Irrigated grain sorghum, winter wheat, and soybeans grown on Pullman soils have the ability to thoroughly dry the profile to about 90-cm depth and to deplete some soil water to the 120-cm depth. Significant depletion below about 120-cm depth usually does not occur due to limited wetting at this depth and the restrictive effect on root development of relatively dense (1.5 to 1.6 g/cm^3) clay Bt subsoil horizons.

This paper reports comparative soil water depletion-grain yield relationships for grain sorghum, winter wheat, and soybeans from experiments conducted on Pullman clay loam at the USDA Southwestern Great Plains Research Center, Bushland, Texas.

PROCEDURE

Grain sorghum data were analyzed from irrigation management experiments conducted during 1956 to 1959 by Jensen and Sletten (1965a), during 1963 to 1965 by Musick and Dusek (1971), and during 1971 by New (1974). The first two studies were conducted in level border plots and involved number, timing, and size of irrigations. The study by New (1974) was conducted in graded furrow plots with variable soil water associated with six length-of-run sampling sites on a 570-m run, three tailwater runoff times (zero with slight lower-end ponding, 3 to 4 and 7 to 8 hr and two seasonal irrigation treatments (two and four applications). There were 36 treatment sites, each replicated twice.

Winter wheat data were analyzed from experiments conducted during 1956 to 1958 by Jensen and Sletten (1965b) and during 1965 to 1967 by Schneider, et al. (1969). Some tests were excluded because of hail damage in 1958 and 1965 and unanticipated stress on the "adequately irrigated" control treatment during late grain filling in 1966.

Soybean data were analyzed from a study by Dusek, et al. (1971) consisting of six irrigation water management treatments and two maturity group varieties, Clark 63 (Group IV) and Hill (Group V). Three water management treatments were based on soil water depletion level and three were based on stage of plant development. The winter wheat and soybean studies were conducted in level border plots.

Soil water was sampled by 30-cm increments to 120- or 180-cm depth before irrigations and at other times during the season. Samples were taken by the gravimetric method for wheat and sorghum and by the neutron method for soybeans. Water retention, determined by Unger (1970) on cores of Pullman clay loam by 30-cm increments to the 120-cm depth, were 10.5, 11.2, 10.7, and 10.7 cm, respectively, at -1/3 bar potential and 6.3, 7.1, 7.1, and 6.8 cm, respectively, at -15 bars potential. Plant available water between -1/3 and -15 bars potential for the 120-cm root zone was 15.8 cm. The crops began the growing season with a relatively wet soil profile, resulting from preseason rainfall and a preplant or emergence irrigation for grain sorghum and soybeans and either a preplant or late fall irrigation for winter wheat.

Experiments were designed to include treatments with a range of stress severity and associated effects on yields. Increasing stress severity was usually obtained by deleting successive normally scheduled irrigations. The driest the 0- to 120-cm profile was measured during a depletion cycle or stress period was used to relate depletion to yields. Maximum soil water depletion data resulted from sampling the day before an irrigation that terminated a stress period or during grain hardening near physiological maturity for treatments where stress continued through grain filling. Additional experimental

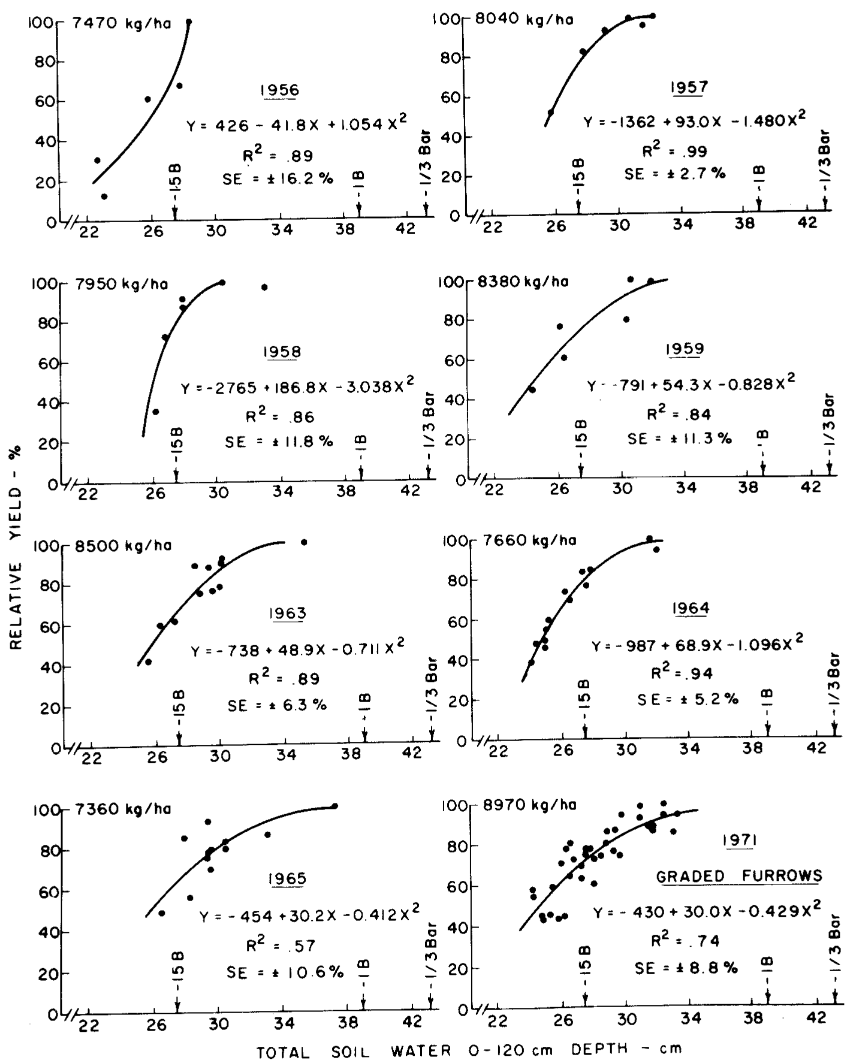

FIG. 1 Relationship of soil water depletion in the 0- to 120-cm depth to relative yields of grain sorghum during 8 yr of tests.

details were presented in the reports of individual studies (Dusek et al. 1971, Jensen and Sletten 1965a, Jensen and Sletten, 1965b, Musick and Dusek 1971, New 1974, and Schneider et al. 1969).

Regression analysis indicated the relationships between soil water depletion and relative yields were significantly curvilinear because of a diminishing yield response to depletion in the wetter range. Since preliminary analysis had indicated that the general quadratic equation provided a good fit to the data, we used this relationship for all crops.

RESULTS

The relationships between soil water depletion and relative grain yields are presented in Figs. 1 through 4. Because of differences in yields among years and crops obtained from the adequately irrigated control treatment, yields from moisture stress treatments were expressed as a percentage ratio of stress treatment yields to maximum yields obtained from the adequately irrigated control treatment. Examination of soil water data indicated major drying into the 60- to 90-cm depth and usually some depletion into the 90- to 120-cm depth. Therefore, the 0- to 120-cm depth was used as the major root zone and relationships to yields determined for the total soil water in this depth.

Grain Sorghum

Relationships of soil water depletion in the 0- to 120-cm depth and relative grain yields under stress condition are presented for 8 yr in Fig. 1. Adequately irrigated yields during the 8 yr ranged from 7,360 to 8,970 kg/ha. Maximum seasonal stress each year reduced yields to the 10 to 50 percent range.

The general quadratic equations provided curves that flattened out in the wetter range at approximately 100 percent relative yield, except for the major drought year of 1956 when late season moisture stress developed on the "adequate irrigation" control treatment. Hot, dry weather during late grain filling caused excessive depletion which reduced expected yields by about 1,000 kg/ha. The excessive depletion for the high yield treatment resulted in the general quadratic curve being concave upward, while all other years resulted in convex curves.

Grain yields were reduced significantly in all sorghum tests when the total soil water in the 0- to 120-cm root zone was depleted to 27.3-cm corresponding to -15 bars potential. Depletion to this level during the 8 yr resulted in relative yields ranging from 64 to 80 percent and averaging 73 percent. The 8 yr of data adequately represented seasonal rainfall conditions ranging from above average to major drought; however, all years tested had one or more major periods of dry weather and none were unusually wet.

The -15 bar potential value is normally considered to represent the permanent wilting point (Richards and Weaver 1944). The data presented in Fig. 1 indicated that grain sorghum growing under field conditions has the ability to deplete soil water under prolonged stress conditions from 3.1 cm (1959, 1964, and 1971) to 4.6 cm (1956) below the -15 bar value. The ability of grain sorghum to deplete soil water below the -15 bar value is associated with the plant's drought tolerance and its ability to produce some grain under prolonged severe stress.

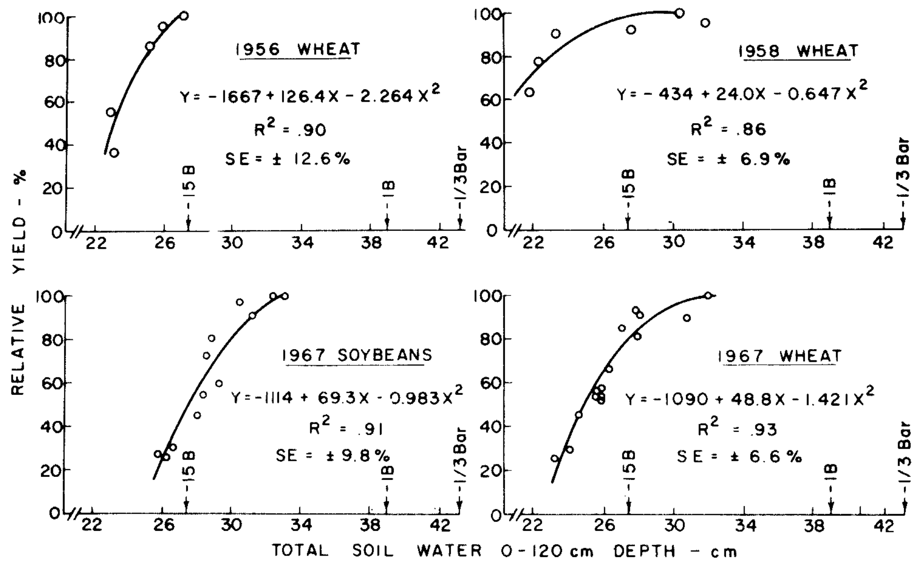

FIG. 2 Relationship of soil water depletion in the 0- to 120-cm depth to relative yields of winter wheat during 3 yr and soybeans during 1 yr.

Winter Wheat

Relationships between soil water depletion and wheat grain yields under stress conditions are presented for three test years in Fig. 2. The best data available for determining the response curve over a wide range of depletion and stress conditions was obtained in 1967 when irrigation treatment yields ranged from 1,180 to 3,960 kg/ha. In the major drought year of 1956, the treatment designated as "adequate water" was allowed to deplete soil water to the -15 bar value. In the above average year of 1958, recurring small rains from March through May largely prevented the development of moisture stress while allowing the subsoil to be depleted of available water. The predominance of cool, cloudy spring weather in 1958 also reduced evaporative demand as compared with the warm dry conditions that prevailed during the spring growth period of the 1956 and 1967 tests.

Depletion of soil water in the 0- to 120-cm profile to the -15 bar value resulted in 80 percent relative grain yields in 1967 and no influence on yields in 1958. The limited data available for wheat indicated that depletion of major root zone soil water potential to -15 bars had less effect on reducing relative yields than the average 73 percent relative yields obtained for grain sorghum. Both winter wheat and grain sorghum are drought tolerant and well adapted to the Southern High Plains. Results from other tests at the Research Center indicated that when the fall-to-early spring weather conditions were favorable, secondary rooting can extend into the 120- to 180-cm depth and some depletion can occur below the 120-cm depth. The less effect of soil water depletion in the 0- to 120-cm depth on yield reduction of wheat compared with sorghum may be related to winter wheat's ability to deplete some soil water from

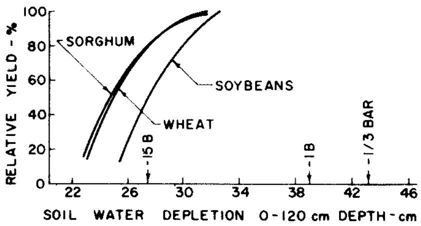

FIG. 3 Relationship of soil water depletion in the 0- to 120-cm depth to relative yield of grain sorghum, winter wheat, and soybeans in drier-than-normal seasons.

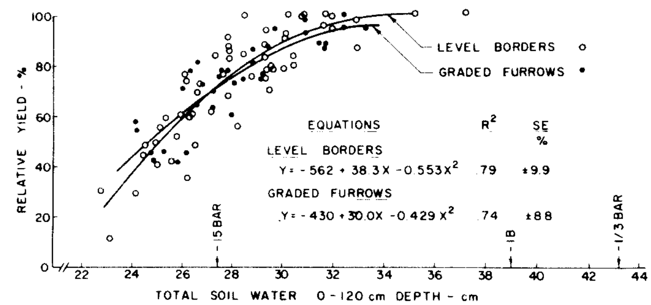

FIG. 4 Relationship of soil water depletion in 0- to 120-cm depth to relative yield of grain sorghum grown in level border plots compared with the relationship obtained from graded furrow plots.

below this depth.

Prolonged stress of winter wheat during the 3 yr resulted in 3.8 to 5.6 cm of soil water depletion in the 0- to 120-cm profile below the -15 bar value of 27.4 cm. This depletion range is about 1 cm greater than was measured during the 8 yr of sorghum tests. Both crops indicated similar ability to deplete soil water in the 0- to 90-cm depth; however, winter wheat indicated greater ability than sorghum to thoroughly dry the 90- to 120-cm depth increment.

Soybeans

The relationship between soil water depletion in the 0- to 120-cm depth and relative yield of soybeans grown under stress conditions in a drier-than-normal season is shown in Fig. 2. Yields ranged from 560 to 2,640 kg/ha. The high yield treatment, which was irrigated when soil water was depleted to 60 percent available in the 0- to 60-cm depth, did not show visual stress and was considered to be adequately irrigated. The depletion relationship was similar in shape to relationships obtained for winter wheat (1967) and grain sorghum (1964) in similar drier-than-normal seasons. However, depletion of soil water under stress reduced soybean yields more than yields of wheat and sorghum (Fig. 3). A comparison of the regression curves for the three similar seasons shown in Fig. 3 indicated that depletion to the -15 bar value resulted in 47 percent relative yield of soybeans compared with 79 percent for wheat and sorghum. The soybean relative yield curve approximately paralleled the wheat and sorghum curves in the 20 to 70 percent relative yield range. For the same relative yield within this range, depletion was 2.7 cm greater for wheat and sorghum than for soybeans. Maximum depletion under prolonged stress was 1.3 cm below the -15 bar value which compared with drier-than-normal seasonal values of 3.3 cm for grain sorghum in 1964 and 3.8 cm for winter wheat in 1967. The ability of sorghum and wheat to deplete soil water to a greater extent than soybeans may result from both crops having fiberous root systems that have greater ability to proliferate the soil mass than the taproot system of soybeans.

Winter wheat and grain sorghum possess excellent drought tolerance and are well adapted to the fine-textured soils of the Southern High Plains. Also, both crops are grown extensively on dryland in the region. Although soybeans were able to deplete soil water to the 120-cm depth, they do not have the drought tolerance of wheat and sorghum and are not grown under dryland conditions in the Southern High Plains.

Level Border-Graded Furrow Comparison

Irrigation water management tests are normally conducted in level border plots to facilitate accurate measurement and uniform distribution of irrigation water, while surface irrigation in the Southern High Plains is predominately by the graded furrow method. The graded furrow test conducted in 1971, with yields ranging from 3,760 to 8,970 kg/ha, provided data for a range of stress conditions for comparison with results from level borders. Soil water depletion-relative yield relationship obtained from graded furrows compared well with the relationship obtained from 7 yr of level border tests (Fig. 4). Therefore, relationships obtained from level borders can be applied directly to graded furrow irrigation on similar soils in the Southern High Plains.

The graded furrow test provided a practical experimental approach to obtaining a large amount of data from fewer field plots. The 570-m furrow length plots were managed to obtain a range of water intake and storage with length of run which resulted in a range of depletion levels within plots sampled as six subplots. Therefore, the six field plot treatments resulted in 36 subplot data points for determining the relationship between soil water depletion and relative yields. Treatments tested in level border studies at the Research Center have ranged from 6 to 16.

DISCUSSION

Since all experiments began the growing season with a relatively wet soil profile, appreciable moisture stress did not develop until about 5 to 6 wk after planting grain sorghum and soybeans and after beginning spring growth of winter wheat. Major stress did not develop until approaching boot stage of sorghum and wheat and beginning of flowering of soybeans. Therefore, the major stress periods associated with reduced yields were during panicle development and grain filling of wheat and sorghum and flowering through pod filling of soybeans. Soil water depletion data with depth indicated generally that plants had a rather well developed root system before appreciable moisture stress developed. Experiments were not designed to evaluate effects of stress in relation to stage of plant development and data analysis did not reveal any consistent major effects within the range of stress periods studied. However, stage of development effects very likely influenced data variability associated with regression relationships presented in Figs. 1, 2, and 4. A second source of significant variability was associated with the amount and distribution of seasonal rainfall, which ranged from 140 to 341 mm and averaged 234 mm for grain sorghum and 229 mm for winter wheat.

Winter wheat and grain sorghum develop good secondary root systems into moist to wet subsoils during vegetative growth. Major soil water depletion can occur during this period before plants encounter sufficient stress to reduce grain yields appreciably. Afternoon visual stress during vegetative growth is usually associated with good overnight recovery so stress effects on reducing yields is limited. Allowing major soil water depletion to the point of developing afternoon stress has resulted in efficient use of irrigation water for grain production.

We did not test yield response to maintaining soil water in the wet range by frequent irrigation. Data from wetter seasons indicated that maintaining higher soil water resulted in little or no additional yield. Frequent irrigation to maintain high soil water contents in level border plots on slowly permeable soils may result in excessive ponding duration and aeration problems not found on graded furrow plots because of good surface drainage.

The greatest soil water depletions measured under prolonged stress conditions were 1.3, 4.6, and 5.6 cm below -15 bars potential for soybeans, grain sorghum, and winter wheat, respectively. If plant available water is assumed to be the difference between -1/3 bar and the minimum points measured for each crop, values for the 0- to 120-cm depth were 17.0 cm for soybeans, 20.3 cm for grain sorghum, and 21.3 cm for winter wheat. Therefore, plant available water exceeded the -1/3 to -15 bar range by 8.3 percent for soybeans to 35.7 percent for winter wheat. The depletion data by wheat, in general, confirmed results by Haise et al. (1955) who found that wheat plants were capable of absorbing soil water at potentials exceeding -26.4 bars at depths where roots were well disseminated.

Knowledge of the range available water, the depletion level when moisture stress begins to decrease yields, and the relationship of continued depletion to reduced yields under stress conditions provides useful information for efficient management and use of water for crop production on irrigated land. Results confirm the general recommendation that 50 percent of plant available water can be depleted from the major root zone of fine-textured soils before significant yield reductions occur.

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